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ENABLER OPERATOR STATION

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ABSTRACT

The objective of this project was to design an on board operator station for the conceptual Lunar Work Vehicle (LWV). This LWV would be used in the colonization of a lunar outpost. The details that follow, however, are for an earth-bound model. Several recommendations are made in the appendix as to the changes needed in material selection for the lunar environment. The operator station is designed dimensionally correct for an astronaut wearing the current space shuttle EVA suit (which includes life support).

The proposed operator station will support and restrain an astronaut as well as provide protection from the hazards of vehicle rollover. The threat of suit puncture is eliminated by rounding all corners and edges. A step-plate, located at the front of the vehicle, provides excellent ease of entry and exit. The operator station weight requirements are met by making efficient use of rigid members, semi-rigid members and woven fabrics.

BACKGROUND

New goals set for the U.S. space program bring back into focus the importance of human exploration of the Moon and, by the 21st century, manned missions to Mars. The primary goal of the Human Exploration Initiative project is to expand the human presence in the solar system by developing sufficient colonies on new worlds and promoting advances in science and technology.[3] An integral part of the new missions will be to establish a permanent manned lunar base. On this base, the astronauts will need to operate outside the boundaries of the colony in order to explore the surface, perform science experiments, mine resources and construct new base structures.

The Apollo mission proved that man could travel to the Moon safely and move around outside the lunar module efficiently. The Apollo Lunar Roving Vehicle (LRV) made the initial surface exploration possible. The LRV, in many ways, was like a desert dune-buggy which could travel at speeds up to 11 miles per hour. The LRV had a 20 mile work radius and the capability to carry all of the necessary sampling tools and rock specimens collected. With the construction of a manned lunar base as an objective of the next lunar missions, an additional vehicle is needed to serve as an all-purpose work machine. The LWV will be responsible not only for the performance of any mechanical tasks but also to support the worker in transit to the work site.

The seats of the lunar rover were problematic in some areas according to the Apollo 15,16 & 17 astronauts.[8] The complaints about the LRV seats included difficulty in mounting and dismounting because the astronauts were required to raise their legs over a vertical distance of one foot to the rover floor, turn and blindly position themselves into seats which were approximately 1.5 feet above the rover floor. In stepping onto the rover, the astronauts kicked up a lot of dust making it difficult to see the instrument panels clearly after repeated ingress and egress. Seat belts of nylon webbing were used as restraints. The belts were latched by threading the webbing through a metal loop. Astronauts had great difficulties performing this maneuver while wearing gloves. During the drive, the seat belts became twisted, which hampered the unbelting process. The seatback angle was awkward because the design of the Apollo suit made it difficult to be comfortable in the normal seated position.

The designers of the rovor seats tried to make good use of Velcro as restraints. This proved disastrous with all of the dust that was kicked up during the movement on the lunar surface. The Velcro also proved to be to strong, making operation difficult. The combination of the webbing design and the Velcro strips on the webbing caused the life support system to become entangled in the seat making dismount awkward.

These problems were taken into consideration in the design of the LWV operator station.

PROBLEM STATEMENT

The design of the lunar work vehicle's operator station must meet the following requirements both on the earth-bound model and the conceptual lunar design:

- support the combined weight of astronaut and current space shuttle EVA suit.
- provide operator restraint system.
- provide rollover protection based on static load of half vehicle weight with appropriate safety factor (4) to account for dynamic loading.
- provide easy access to vehicle controls .
- maintain ease of ingress / egress to operator station
- remain within maximum chassis mounting width on the forward T-section of vehicle.
- meet minimal weight requirements through selection of materials.

The dimensions for this operator station design are based upon the current shuttle suit dimensions due to lack of concrete information on either the Mark III or AX-5 suit:

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• helmet height:	381 mm
• shoulder width:	726 mm
• seat height- foot to buttock:	508 mm
• primary life support system height:	813 mm
• shoulder height-seated:	940 mm
• seated height to top of helmet:	1016 mm
• arm reach:	813 mm

(These dimensions are given in detail in appendix A.)

DESIGN DESCRIPTIONS

The seat design is divided into three categories: structure, fabric, and restraint. The actual designs for each of these categories is discussed in detail in sections that follow. The design process, including alternates and decision matrices, is included in the appendice.

Structure

The actual seat structure consists of the roll cage and the step plate support mounted to the front of the T-section. Also considered was the material selection and the mounting mechanism to the chassis.

Roll Cage: Design

The primary consideration for the main structure of the operator station was to protect the operator in the event of a vehicle rollover. In order to provide such protection, the structure of the operator station was designed similar to a roll cage used in automobile racing. The general design consists of a slanted U-shaped main hoop with two vertical support bars (See figure 1). The front T-section of the vehicle is about 1067 mm wide, which allows the hoop to be designed with a wide-radius, thus producing only simple curves.

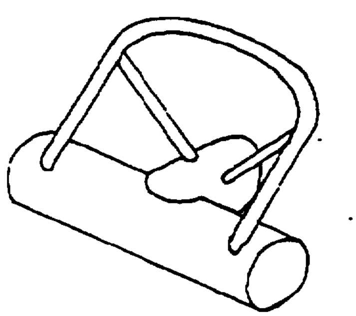


Figure 1
U-shaped Roll Cage Design

While this configuration would be preferred, integrating this design with the basic model of the Enable forced a redesign. In redesigning the Roll Cage the width given for mounting on the forward T-section was kept in mind. On the forward T-section, the wheel drives and their hubs are designed to detach easily from the central chassis section. This arrangement requires that the roll cage attach only to the central section of the chassis. The width at this point is approximately 510 mm. After allowances for welding, attachment hardware and tool clearances, the usable width of the front T-section is roughly 460 mm. This is a limiting factor which forced design modifications as seen in figure 2.

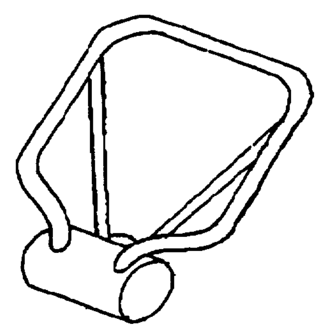


Figure 2
Roll Cage designed to meet mounting limitations

Roll Cage: Material Selection

Preliminary materials selection was based on the standards specified by automobile racing sanctioning bodies, NHRA and NASCAR. Roll cage standards were consulted and found to specify either mild steel (AISI 1020 or 1018) or stainless steel (AISI 4140). Since steel is in widespread use and is cheaper and easier to work than composites involving carbon. Steel was selected for this design.

After examining the tubing sizes specified for racing roll cages, a tubing manufacturer was consulted for information about available materials, diameters, and wall thicknesses. Reasonable tubing sizes, which are commercially produced, are those with outside diameters from 31.75 to 76.20 mm (1.25" - 3"). Available wall thicknesses for such tubing range from 2.11 to 3.96 mm (0.083" - 0.156"). The minimum bend radius specified for the design is five times the nominal diameter of the tubing. This factor of five results in a minimum bend radius which can easily be accomplished in most standard metal working facilities.[14]

ASTM data on the 1020 steel rated a yield strength of 262 MPa and 4140 steel a strength of 620 MPa. Because of the higher yield strength, 4140 stainless steel was specified for the design. In this application, the safety and space requirements were judged more important than the increased cost and difficulty created by using stainless steel.

In order to determine material strength requirements and determine final dimensions, a finite element analysis of the structure was performed. ALGOR software was used to prepare a model and analyze its performance. Due to constraints of the software used, each curved member was approximated as two separate straight tubular segments. Several design refinements based upon information from the models were incorporated into the final chosen design.

The forces used in this analysis were based on the assumption that static loads of half the vehicle weight [approximately 5300 N (1200 lb.)] were acting upon the roll cage. The actual dynamic loads on the roll cage were considered by designing for a safety factor of four. A 5300 N force was placed at six locations oriented along the roll cage. The highest resultant stresses occurred in the case of a horizontal force, acting sideways, located at the top of the roll bar (see the analysis in appendix A).

The finite element analysis was performed for various tubing sizes. The results indicated 76.2 mm outer diameter tubing with a 3.05 mm wall thickness as the most appropriate choice. Using 4140 steel results in a maximum stress in the structure of 143 MPa, a safety factor of approximately 4.3. While smaller diameter tubing may be lighter in weight and more normal in appearance, any tube sizes below 50.8 mm with a 3.96 mm wall thickness cannot withstand the forces which act upon the structure. A choice of 50.8 mm tubing with 3.96 mm wall thickness material results in a safety factor of only 1.8. This was regarded as too small a margin for a human safety application where the true forces are not known.

The force analysis also showed that the highest stresses in the tubing occur near where the roll cage connects to the chassis. Thus, the design of the structure above the attachment points was not critical from a stress standpoint. The structure at the top of the roll cage was therefore designed for astronaut clearance in ingress/egress and minimal tubing use for minimal weight of the structure. Other structural configuration attempts yielded negligible improvements in reducing the critical stress near the chassis attachment points.

Seat Frame

The actual seat and backrest for the operator station are supported by 6.35 mm diameter steel cable held by eyelets which are welded to the roll cage. The steel cable has a load limit of 6228 N (1200 lbs), which easily supports the estimated operator weight of 890 N (200 lbs). For the seat and backrest, cable was chosen instead of steel tubing for all structural members in tension because of its lighter weight. The cable passes through an eyelet and is fastened to itself with standard cable ties. The seat and backrest also include a cotton twill fabric, which is discussed in section 8.4.2

Step Structure Design

Because of the height of the vehicle and the mobility restrictions upon a suited astronaut, a step is required for ease of ingress/egress to the operator station. This step was integrated into the operator station design by placing it immediately forward of the front T-section. The size of the plate was based upon the competing requirements of ease of ingress/egress and minimum weight. Operator ingress is accomplished by stepping onto the plate, turning around on the plate, and then sitting in the seat. The roll cage main hoop is used for position and orientation references during this action.

The step-plate is supported by steel tubes which connect it to the front T-section. The loads produced when an astronaut steps upon the plate are quite severe because of the long moment arm to the chassis attachment. A finite element analysis of the step-plate and its supports was performed in order to specify the tubing size. The same range of tubing diameters (31.75 - 76.20 mm) and wall thicknesses (2.11 - 3.96 mm) as for the roll cage was considered.

A final design of a 31.75 mm outside diameter tubing with a 3.96 mm wall thickness was chosen for the supports of the step plate. When a 1000 N (225 lbs) load is applied at the corner of the step plate, a maximum stress of 358 MPa develops in the supports. Because of this high stress value, AISI 4140 steel was chosen for the support tubes. With this material, a safety factor of 1.7 results for this load. While this safety factor is lower than that of the roll cage, the step plate is not critical to the safety of the operator. An additional consideration is that the use of larger diameter tubing would have resulted in insufficient leg space for a suited astronaut.

The step-plate itself was designed of 6061-T6 aluminum for its superior strength to weight ratio compared to that of steel. It is bolted to the support arms using standard grade 5 bolts and washers.

Attachment to Chassis

The nature of rollover loads greatly complicates the attachment of the roll cage to the chassis. While dynamic loads are difficult to predict, the obvious static load in the event of a rollover is the weight of the front half of the vehicle. Therefore, the weight of the chassis must be transferred to the roll cage so that the operator will not be crushed. As a result, the connections between the roll cage and the chassis must support not only the weight of the roll cage but also the weight of the front of the vehicle.

The roll cage and step structure are welded to thin steel pads which distribute the point loads over a greater area. The pads are then welded to the skin of the chassis structure. Since that skin is relatively thin and would deflect under such distributed loads, a system of load carrying bulkheads were designed into the front chassis T-section.

The use of steel for the chassis T-section as well as the roll cage and step structure allows the assembly to be welded together. Standard TIG welding procedures for joining steel to steel can be implemented using a standard fillet weld to join the pipes. A weld depth of 3 mm was specified based on the welding of pipe of 3 - 4 mm wall thickness.[2]

Fabric

The operator station's seat will have fabric in two locations on the structure, the backrest and the seat. The fabric will be looped around each cable and double-stitched to itself with polyester/cotton thread.

In choosing the fabric, several factors were taken into consideration. First, the fabric must be strong enough to support the entire weight of astronaut. It must also have low elongation so that it will not creep or deform. Finally, cost and availability play a major role in the fabric selection.

For this design, a cotton twilled fabric will be used. This decision is based on the availability and cost of this type of fabric.

The fabric dimensions and shapes for the seat are given in the following figures.

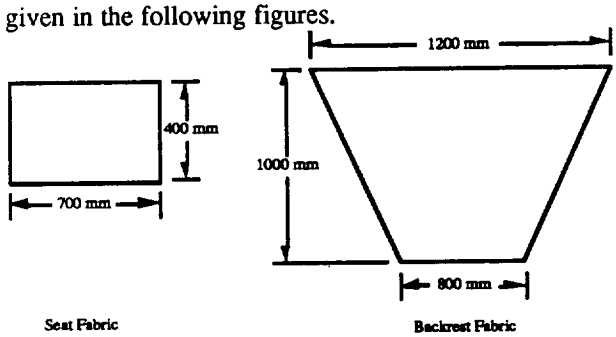


Figure 3
Fabric Dimensions and Shapes

Restraint

After considering a number of complicated seat belt designs, an aircraft-style lap belt was selected as a preliminary design. At low speeds, this type of lap belt, together with the contoured seat design should adequately restrain the astronaut. Also, the addition of an upper body restraint would hamper the astronaut's ingress/egress.

The restraint will be attached to the chassis by using the clip, already attached to the seat belt, and a eyelet that will be welded to the chassis near the seat attachments.

Weight of Operator Station

The weight of the operator station, as described above, complete with mounting hardware is approxiamately 55 kg.

CONCLUSIONS AND RECOMMENDATIONS

The initial goal for this project was to design an operator station for the lunar work vehicle which would meet dimensional considerations of a suited astronaut and provide rollover protection. The design described in this report and supporting technical drawings list (see appendix A) meet these requirements. While the design meets the constraints previously listed, further modifications could improve the existing design.

First, a re-analysis should be done on the roll cage of the operator station. The first recommendation would be to analyze the roll cage structure using materials other than steel. Other materials (aluminum, carbon fiber composites, etc.) would allow a lighter weight structure with potentially smaller tubing sizes to be developed. Also, the utilization of the Algor FEA system requires each member to be approximated as a straight tubular member. The number of members which approximate a curve could be increased to improve the accuracy of the FEA results.

Before some of the analysis can occur, the building of a full scale model is necessary. The actual ingress/egress of the suited astronaut needs to be investigated. Along with this, the structural integrity of the cable needs to be analyzed. The loaded shape of the fabric and cable must be studied experimentally. Depending on fabric thickness, the present design should be adequate; however, a mathematical analysis should be performed to determine the actual tensile loads present in the fabric and on the structure. In the analysis of the fabric of the seat, the actual pressure distribution caused by the astronaut should be investigated.

The restraint used in this design could also be improved. While this style of restraint (single lap belt with aircraft-style buckle) would work well, a larger size buckle would allow easier manipulation by the suited astronaut. Another style buckle to consider is similar to the handle-pull type used by tree climbers. Additionally, some type of spring or stiffer webbing should be used to hold the seat belt in an upright position to aid the astronaut in locating the belts.

APPENDIX A:
DESIGN PROCESS

Table A.1: Decision Matrix for Seat Design Selection

FACTOR	MAX SCORE	DESIGN A	DESIGN B	DESIGN C	DESIGN D
Weight	30	18	30	16	18
Ease of Chassis Attachment	10	10	10	4	6
Ease of Restraint Integration	10	10	6	6	10
Rollbar Integration	10	10	1	10	10
Operator Support	15	15	5	10	15
Comfort	5	4	3	2	5
Ingress / Egress	20	18	16	20	12
TOTALS	100	**85**	**71**	**68**	**76**

STRUCTURE

After conducting research and gathering ideas from the design team, four preliminary seat designs were chosen for the final structure. The best one of the four designs was determined in the decision matrices shown below in Table 1. The sketches of each of the designs follow.

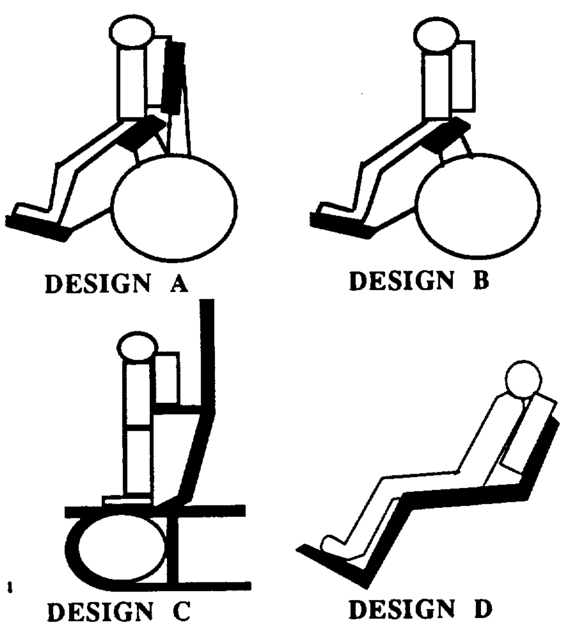


Figure A.1

Design A received the best score in the decision matrix. This design was further studied, analyzed, and revised into the solution presented in this report.

FABRIC

In selecting the fabric for the earth-bound rover, the primary considerations were cost, availability, and performance. Cotton was readily available at no cost. The relevant properties of cotton are:

- density = 1.54 g / cm^3
- 7% elongation
- tenacity = 4 g / denier

Tenacity is the tensile strength of a fiber expressed as a force per unit of linear density of an unstrained specimen. It is usually expressed in grams per denier or grams per tex.

- Tensile strength (in psi) of cotton fabric:

TS = tenacity x density x 88.3

where: Tensile Strength of fiber (MPa)
Tenacity (g / denier)
density (g / cm^3)
88.3 = conversion factor

{1000 psi = 6.895 MPa}
TS(MPa) = 4 x 1.54 x 88.3 = 543.9 MPa
TS(psi) = 543.9 MPa x (1000 psi / 6.895 MPa) = 78887 psi

Strength of yarn ≈ 0.8 strength of fiber
Strength of woven ≈ 0.9 strength of yarn
Strength of yarn = 0.8 x 78887 psi ≈ 63110 psi
Strength of fabric=0.9 x 63110 psi ≈ 56800 psi

As a result, this tensile strength should be sufficient to withstand any tensile loads produced by the seated astronaut.

SPACESUIT DIMENSIONS

The most important factor is the design of the operator station is with the dimensions of the suited astronaut that the station is built for. The design is built around the current space shuttle EVA suit. This suit was chosen because other Lunar/Mars suits are still in the design phase, making the dimensions and functions of these suits uncertain.

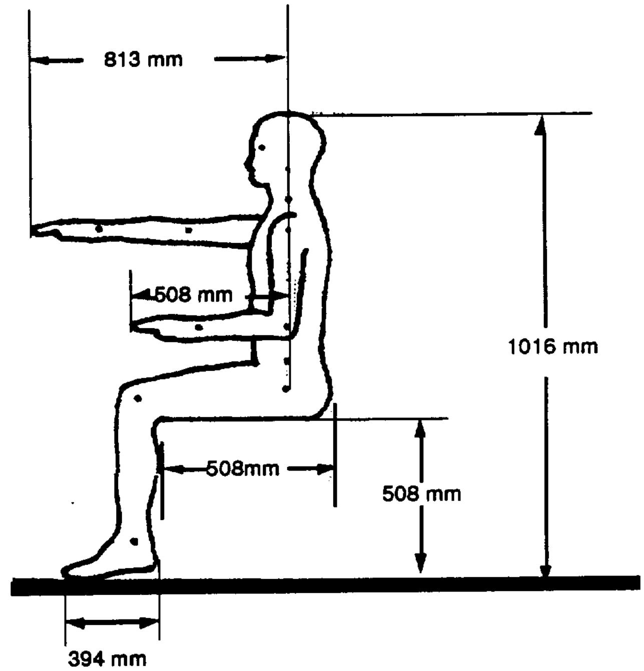


Figure 8A.2 Seated Dimensions

Table 8A.2: Mobility Ranges*

MOVEMENT	SHUTTLE	Mk III	AX-5
Forward/Upward Reach	EXCELLENT	GOOD	GOOD
Backward Torso Bending	GOOD	FAIR	FAIR
Forward Torso Bending	FAIR	FAIR	GOOD
Straight Leg Hip Flexion(R)	FAIR	GOOD	GOOD
Straight Leg Hip Flexion(L)	FAIR	GOOD	GOOD
Bent Knee Hip Flexion(R)	FAIR	GOOD	EXCELLENT
Bent Knee Hip Flexion(L)	FAIR	GOOD	EXCELLENT
Overhead Reach from Side	GOOD	GOOD	EXCELLENT
Inboard Chest Reach	GOOD	GOOD	EXCELLENT
Arm Sweeping Motion	GOOD	GOOD	EXCELLENT
Torso Rotation	GOOD	FAIR	EXCELLENT

*This information was taken from a proprietary document, therefore numbers were not used.

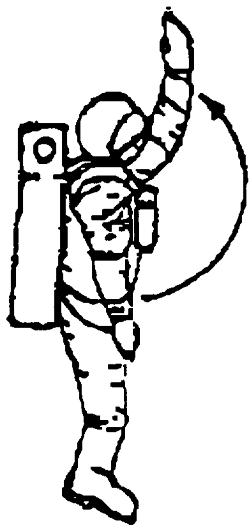


Figure A.3:Forward/Upward Reach

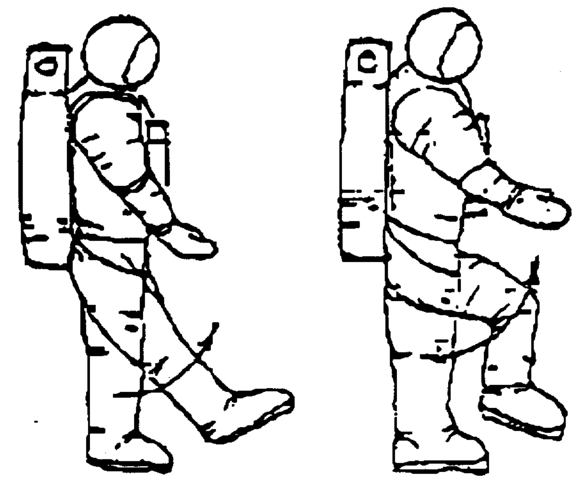


Figure A.6: Straight Leg and Bent Knee Hip Flexation

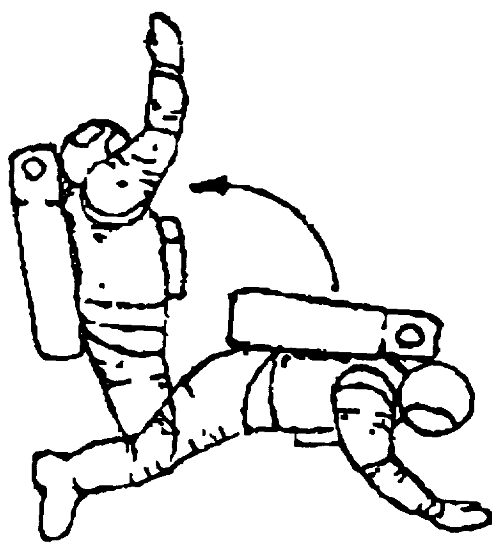


Figure A.4: Backward Torso Bending

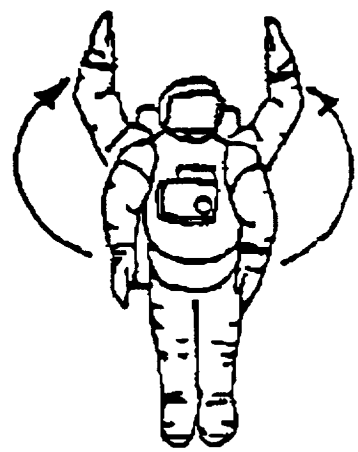


Figure A.7: Overhead Reach

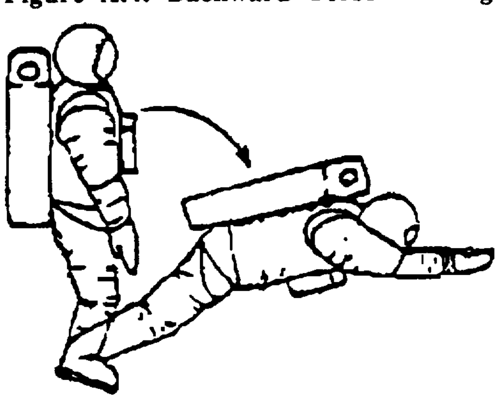


Figure A.5 Forward Torso Bending

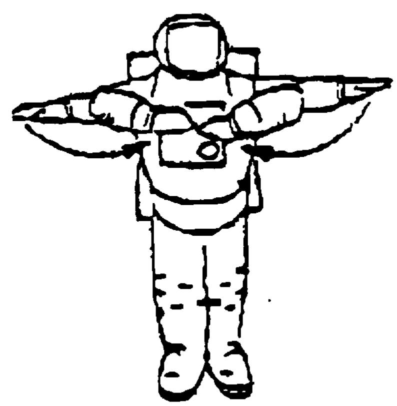
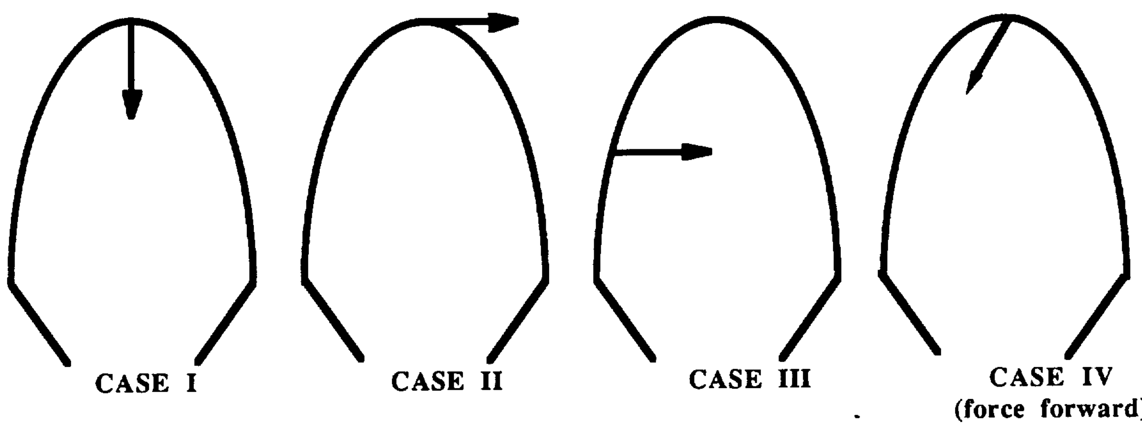


Figure A.8: Inboard Chest Reach from Side

A.4 FORCE ANALYSIS FOR STRUCTURE

Table A.3: Loading Analysis

LOAD CASE	MAXIMUM DEFLECTION (mm)	MAXIMUM STRESS (MPa)
I	1.4	69
II	4.76	114
III	4.20	105
IV	4.01	111
V	4.01	111
VI	0.062	61



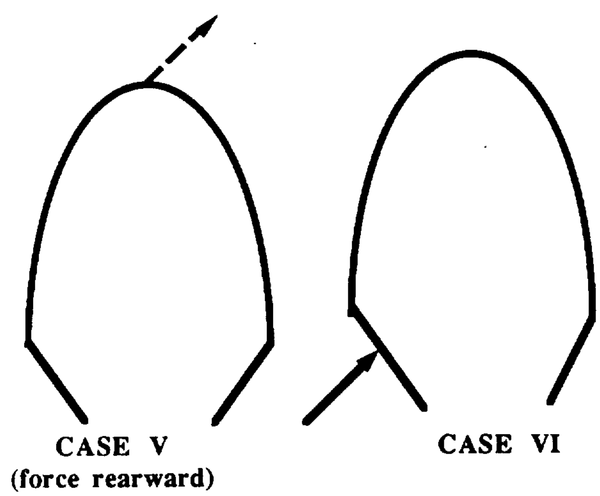


Figure 8A.9 Case Loads

Section 1 - Roll Cage

The numbers shown in table 8A.3following are for 76.2 mm tubing with 3.96 mm wall thickness

For tubing of this size, the worst load case from the figure shown was:

Load Case II: Max. deflection = 5.97 mm, Max stress = 142 MPa.

All other load cases are assumed to give lower maximum stresses than 142 MPa for the thinner wall tube (3.05 mm), following the trend of the thicker wall tube (3.96 mm).

Section 2 - Step Structure:

For a 31.75 mm tube, a 1000 N (225 lbs) force was applied downward on the end of the step structure assembly :

Table A.4 Step Structure Analysis

WALL THICKNESS (mm)	MAXIMUM DEFLECTION (mm)	MAXIMUM STRESS (MPa)
3.05	9.01	426
3.96	7.57	357

Table B.1 Fiber Properties

Fiber Type	Maximum Temperature (F)	Density (g/cm^3)	% Elongation	Tenacity (g/den)
Kevlar 49	932	1.44	2.5	23
Nomex	572	1.38	22	5.3
PBI	1112	1.43	30	2.7
Spectra 1000	300	0.97	2.7	35
Nylon DuPont 728	250	1.14	18.3	9.8
Glass Fiber	1346	2.5	3.1	9.6

APPENDIX B: SUGGESTIONS FOR LUNAR MODEL

LUNAR ENVIRONMENT

The harsh conditions of the lunar environment, necessitate changes to the design. The lunar environment is such the temperature range is approximately ±120 C° (±250 F°). Lacking an atmosphere, the surface of the moon is struck by unfiltered ultra-violet radiation, so any material used must be considered with respect to this factor.

STRUCTURE RECOMMENDATIONS

Section 1 - Roll Cage & Step Structure

For a lunar mission and the extreme transportation expenses of such a venture, the weight of the structure becomes much more important. As a result, composite structures would probably be investigated. One possible configuration is composite-reinforced straight tubes connected by reinforced elbows. The tubes could be made by winding glass-fiber/epoxy reinforcement over a thin aluminum skin. The elbows could be made by reinforcing aluminum elbows with glass-fiber and epoxy tape.

A thick layer of filament-wound glass fiber reinforcement around an aluminum skin would provide a high-strength, low weight material. Possible materials for such a construction include Owens-Corning 250 yield S2 fiberglass and 6061-T6 aluminum. If a similarly large diameter tube structure is allowable, 76.2 mm diameter round tubing of 1.59 mm wall thickness could be surrounded by 6 mm of lament-wound glass-fiber and epoxy in a $[(\pm 20°)_6(90°)]_3$ lay-up pattern. This structure would greatly reduce the weight of the roll cage or greatly increase its factor of safety.[9]

There may be a reduction in the design loads when the one-sixth gravity of the moon is considered.

Section 2 - Seat

As in the structural design, weight becomes the overriding constraint on the design of the seat. For this reason, advanced materials will probably be substituted in this area as well. The steel cable used for the seat and backrest could be replaced by an advanced fiber rope. The major problem with the lunar environment from this point of view is the ultraviolet radiation present there, which would severely degrade polymer products. Either glass-fiber alone or a polymer in combination with an aluminized coating could be substituted for the current steel cable.

Section 3-Fabric

The fabric selection for the a lunar would entail the use of Kevlar/Nylon in a basket weave. A basket weave which has high tear strength in both its lengthwise and widthwise direction would use Kevlar for its strength and Nylon for its flexibility.

Unfortunately, with any polymer chosen , the effects of ultra-violet radiation would cause significant in damage to the fabric. Any recommendation involving the use of a polymer must include UV protection; the one recommended is aluminized mylar. The application of the mylar can be in the yarn or fabric formation.

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